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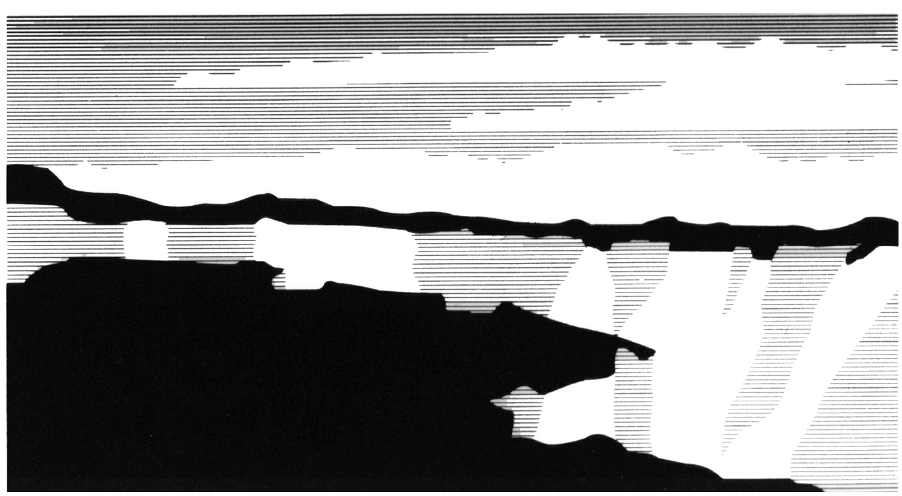

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Urban parameterizations for mesoscale meteorological models

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Abstract

Urban parameterizations developed for use in mesoscale meteorological models are described. These parameterizations attempt to account for the area-average effect of drag, turbulence production, heating, and surface energy budget modification induced by buildings and urban landuse. Some insights garnered through field observations regarding the urban influence on local meteorology are given, including short descriptions of the urban heat island and urban roughness. A brief survey of prior work on mesoscale modeling of urban areas is presented. Finally, problems that arise when implementing or validating the urban canopy parameterizations are discussed.

1. Introduction

Cities impact the local weather by perturbing the wind, temperature, moisture, turbulence, and surface energy budget fields. Buildings alter the wind, produce turbulent eddies, create shade, and trap heat. The urban fabric – made up of such materials as concrete, asphalt, and steel – stores and releases heat differently than rural areas. Energy consumption related to home and office heating and cooling, manufacturing, and transportation releases heat to the urban environment. Cities in arid environments may be wetter than their surroundings due to high water use, while cities in humid environments may be dryer due to replacement of natural vegetation with urban materials. Urban-rural thermal differences can lead to generation of winds.

Numerous investigations have shown that buildings and urban landuse significantly modify the micro- and mesoscale flow fields (e.g., see reviews by Bornstein [1] and Hosker [2]). Accounting for the urban impact on atmospheric dynamics and thermodynamics is important for many applications, e.g., urban photochemical modeling, plume transport and dispersion, wind loading on buildings studies, urban design and energy usage studies, thermal comfort level evaluations, global warming assessments. For example, a plume trajectory may be modified by urban heat island circulations, the transport speed may be reduced due to building-induced drag, and vertical mixing might be enhanced as a result of heat island convection or building-created turbulence. For air quality applications and accidental release scenarios, mesoscale numerical models are often used to provide meteorological fields to air chemistry and puff dispersion models or boundary conditions to higher resolution models. Since mesoscale models do not have the spatial resolution to directly simulate the fluid dynamics and thermodynamics in and around urban structures, urban canopy parameterizations are sometimes used to approximate the drag, heating, radiation attenuation and enhanced turbulent mixing produced by the sub-grid scale urban elements.

In this chapter, we will focus on current methods for incorporating urban effects into mesoscale models. We will cover techniques for incorporating drag and turbulence production into the flow equations and modifications to the surface energy budget and heat equation to account for urban influences. We will distinguish between methods intended for use *above* the urban canopy from those intended to be used *within* the canopy. By necessity, we will present a short review of urban effects on mesoscale flows and will give references to more thorough reviews. We will end with a section on implementation and practical difficulties associated with the urban parameterizations, namely parameter specification and model validation issues. We will not cover the specifics of atmospheric dispersion in urban environments. We point the interested reader to very good reviews of urban impacts on dispersion by Hanna and Chang[3], Hanna et al.[4], Hosker[5], Yamartino et al.[6], and Brown and Streit[7].

2. Urban canopy impact on mesoscale flow

In the 1960's and 70's, the atmospheric sciences community began looking seriously at how cities impact the natural climate system (e.g., Chandler[8], Daigo and Nagao[9], Landsberg[10], Oke[11]). In the 1970's a number of groundbreaking urban field experiments were conducted, partially in response to air quality concerns in large metropolitan cities (e.g., Bornstein[12], Clarke[13], Ludwig[14], Oke and East[15], Angel et al.[16], Ackerman[17]). Likewise, in the late 60's and early 70's, computer models were first being used to understand the dynamics of urban-induced circulations and heating patterns (e.g., Myrup[18], Atwater[19], McElroy[20], Bornstein[21]). Based on these field experiments and numerical model results, the urban climate system was found to be multi-dimensional and complex with numerous feedback mechanisms between components. Explanations were hypothesized as to why many cities were warmer at night than the surrounding rural areas (coined the "urban heat island") and urban-scale flow patterns were found that were associated with these thermal differences. In addition, it became apparent that the drag and turbulence created by the "roughness" of buildings were large enough to reduce the strength of the mesoscale wind and enhance boundary-layer-scale mixing. In the next two sub-sections, we give short reviews of the so-called urban heat island and urban roughness effects. Our main purpose here is to identify the general flow features and mechanisms that are important to simulate and/or account for in mesoscale models. More complete accounts can be found in the excellent reviews by Oke[22] on the urban surface energy budget, by Bornstein[1] on urban circulation and thermodynamic evolution, and by Oke[23] on urban climate modification.

2.1 Urban heat island

The well-known urban heat island phenomenon is characterized by warmer temperatures in the city as compared to the surrounding rural area. Generally, the heat island occurs at night and results because the rural area cools faster than the urban area. Urban heat islands can induce thermodynamically driven urban-scale flows. In calm or low wind

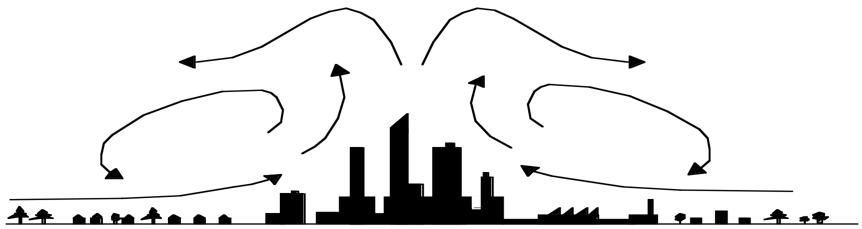

Figure 1. Illustration of urban heat island circulation during calm wind conditions. Pressure differences resulting from warmer temperatures in the city and cooler temperatures in the surrounding rural area lead to thermally-driven flows. Adapted from Lowry[24] and Liu et al.[25].

conditions, the warmer air in the city core rises, pulling air near the surface radially inwards (Fig. 1). A radially outward return flow may develop aloft. A dome of heated air often forms above the city. For slightly stronger ambient winds, a plume of heated air may extend downstream of the city.

Figure 2 shows temperature measurements at the surface for Okayama City, Japan and reveals the urban heat island signature. Temperatures are highest near the core of the city, where buildings are tall and urbanization is dense. Temperature differences of up to 10-12 K have been measured across large cities (Oke[23]). The vertical structure of the urban heat island often shows a several hundred meter well-mixed layer, as

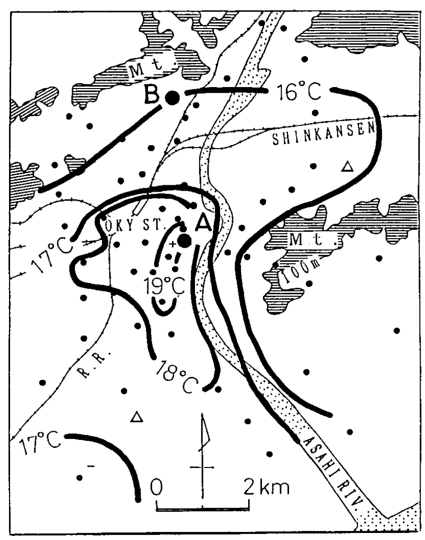

Figure 2. Surface temperatures observed at 21:00 local time for Okayama City, Japan. The hotter core is centered over the downtown area. From Sahashi et al.[26].

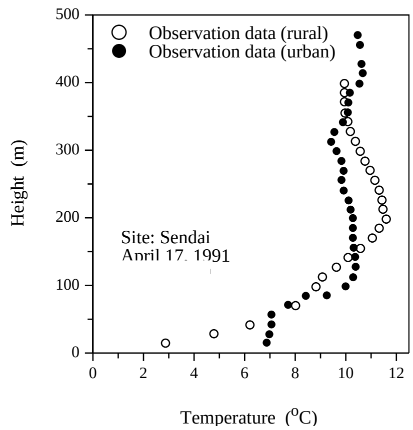

Figure 3. Nighttime temperature profiles at urban and rural sites reveal the heat island well-mixed layer. Adapted from Saitoh et al.[27].

indicated in Fig. 3. Here, a vertical profile of temperature outside of Sendai, Japan shows a deep stable layer, while the profile over the city reveals that the air temperature is uniform up to 50 meters and is warmer near the surface relative to the rural profile. Vertical profiles of the average of many urban-rural temperature difference measurements are given in Fig. 4 for the cities of New York, Christchurch, and Montreal. The profiles show a heated region extending from the surface to between 300 and 800 meters above the cities.

There have been fewer field measurements of the thermo-

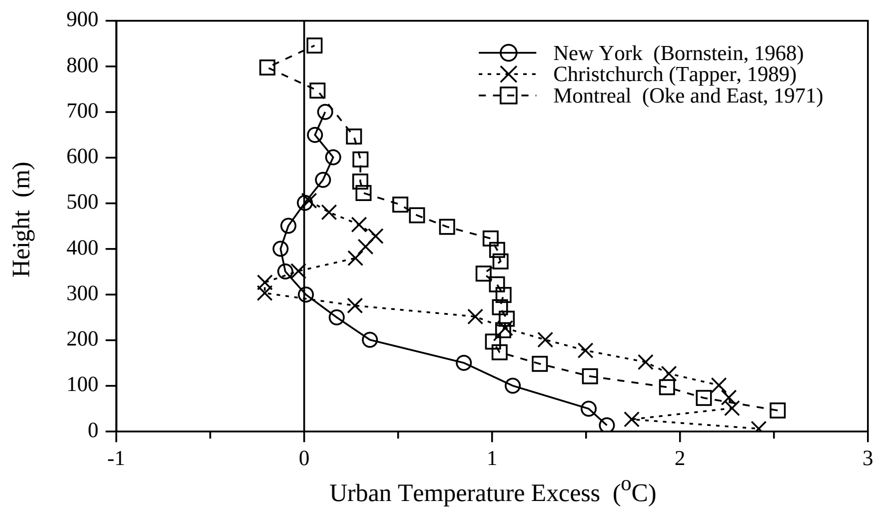

Figure 4. Average urban-rural temperature difference as function of height for 3 cities near sunrise. Adapted from Tapper[28].

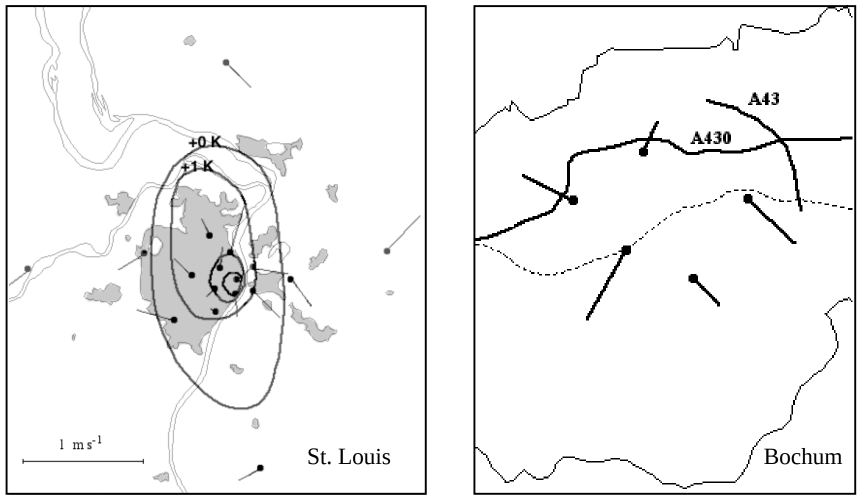

Figure 5. Urban heat island induced winds over St. Louis, USA and Bochum, Germany. Adapted from Shreffler[29] and Kuttler and Romberg[30].

dynamically-driven winds, in part because of the difficulty of separating the large and small scale components of the wind circulation. Climatological averages of surface wind sensor data in St. Louis, USA (Shreffler[29]) and Bochum, Germany (Kuttler and Romberg[30]) reveal radial inward motion (Fig. 5). These climatological averages were obtained during low wind speed conditions and in the former case by subtracting off the assumed prevailing wind components.

Although urban heat island intensity as measured by the maximum temperature difference between urban and rural sites correlates well with population, Oke's[31] review of existing measurements showed that European and North American cities collapsed onto two different curves (Fig. 6). Further analysis suggested that the difference was caused by the relatively taller buildings in the core of American cities. Figure 7 shows the urban heat island intensity plotted as a function of building height-to-width ratio, one measure of urban density. It should be pointed out that these data are for calm wind and cloudless conditions.

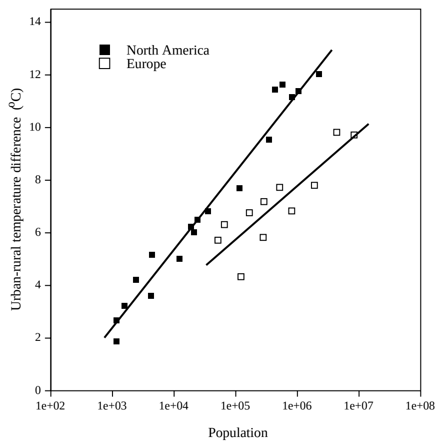

Figure 6. Measurements of urban heat island intensity as function of population showing differences in European and N. American cities (adapted from Oke[31]).

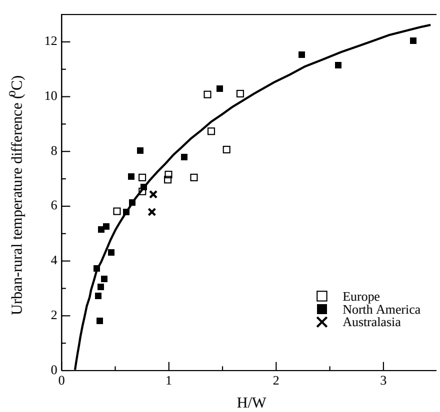

Figure 7. Measurements of urban heat island intensity as function of building height-to-width ratio (adapted from Oke[31]).

Although the measurements tend to collapse fairly well, results from numerous studies suggests that the formation and evolution of the urban heat island is complicated, dependent on a number of competing factors. For example, Fig. 8 indicates that the urban–rural temperature difference is a strong function of wind speed. If the winds are too strong, the heat can be advected away faster than it can be replenished by the city. In fact, Oke and Hannell[32] proposed that there is a critical wind speed above which urban heat islands do not form. They found that the critical wind speed U_c was a function of population P:

$$U_c = 3.4 \log P - 11.6 . \quad (1)$$

Relationships like those shown in Figs. 7 and 8 and eqn. (1) will be useful for direct testing and validation of mesoscale meteorological model results and indirect testing of the urban parameterizations.

Differences in the surface energy budget between urban and rural locales are suspected of being primary factors in the formation of the urban heat island. The energy balance in a control volume containing the urban canopy can be written as (Oke[22])

$$\begin{aligned} Q^* + Q_F &= \left(R_{L\downarrow} - R_{L\uparrow}\right) + \left(R_{S\downarrow} - R_{S\uparrow}\right) + Q_F \\ &= \Delta R_L + (1-\alpha) R_{S\downarrow} + Q_F \\ &= Q_H + Q_E + \Delta Q_S + \Delta Q_A \end{aligned} \tag{2}$$

where Q^* is the net radiation, Q_F is the anthropogenic heat flux, $R_{L\downarrow}$ and $R_{L\uparrow}$ are the downward and upward longwave radiation, respectively, $R_{S\downarrow}$ and $R_{S\uparrow}$ are the downward and upward shortwave radiation, respectively, ΔR_L is the net longwave radiation, $(1-\alpha)R_{S\downarrow}$ is the net shortwave radiation, α is the surface albedo, Q_H is the sensible heat flux, Q_E is the latent heat flux, ΔQ_S is the energy storage in the canopy, and ΔQ_A is the advection of energy into and out of the control volume. The net radiation represents the amount of energy coming into ($Q^* > 0$) or out of ($Q^* < 0$) the canopy from short and longwave sources. The energy associated with the net radiation and the anthropogenic heat flux is partitioned into the sensible heat flux (heats or cools the air), latent heat flux (evaporates water or condenses water vapor), energy storage (heats or cools urban surfaces), and advective heat flux (represents the energy transported by the wind into or out of the canopy volume). Later in Section 3.5 we will discuss eqn. (2) in more detail and present a slightly different form that we feel is more useful for mesoscale meteorological model implementation.

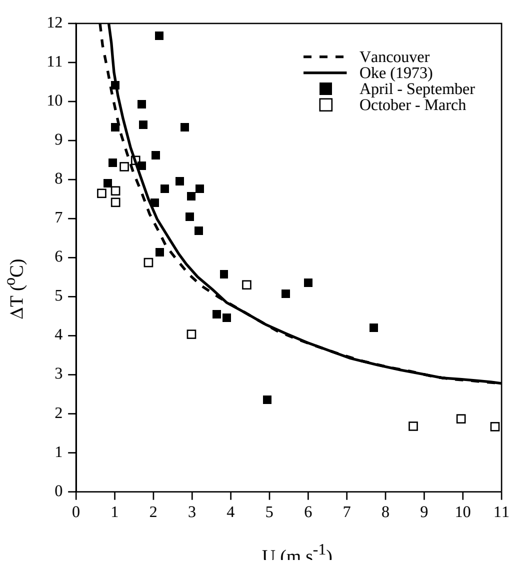

Figure 8. Measurements of heat island intensity plotted as a function of wind speed (adapted from Oke[33]).

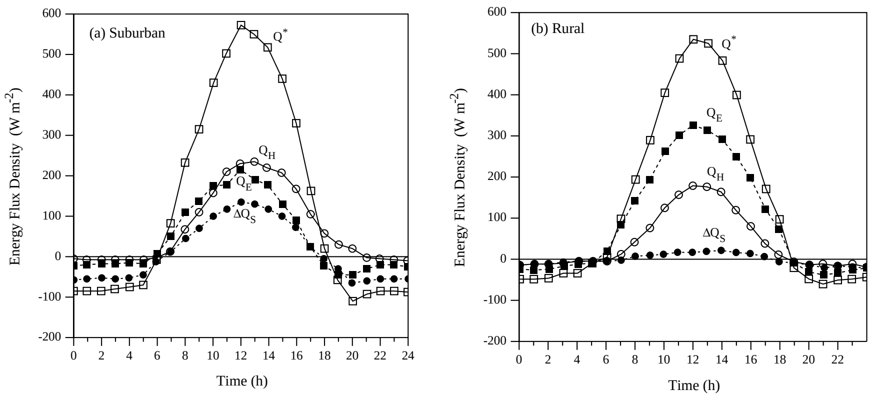

Figure 9. Surface energy balance measured over 30 days during the same time period at suburban and rural sites in Vancouver, BC (adapted from Oke[22]).

Figure 9 shows a diurnal cycle of surface energy fluxes for a suburban and a rural site in Vancouver. A number of major differences are apparent. First, the latent heat flux Q_E is much larger during the daytime at the rural site, indicating that the rural surface has more moisture than the suburban surface. Second, the canopy storage term ΔQ_S is much larger during the daytime at the suburban site, implying that the suburban canopy has more energy storage capacity. Third, the sensible heat flux Q_H remains positive for a few hours after sunset at the suburban site and the canopy storage term ΔQ_S reverses sign at night (i.e., the canopy mass gives off energy to the atmosphere) becoming relatively large in magnitude at the suburban site. This additional input of energy into the atmosphere helps to explain why the rate of cooling at night is smaller in the urban area and why temperatures would be warmer there. Additionally, the lack of a strong heat island during the daytime, which one might expect due to the small fraction of the net radiation Q* that goes into latent heating in the suburban area, is partially explained by the relatively large fraction of net radiation that goes into heating the canopy elements (ΔQ_S), thereby reducing the amount of energy that goes into heating the air (Q_H) in the suburban area.

Oke[22] lists seven (sometimes competing) causes for why cities may become warmer than the surrounding rural areas: 1) decreased longwave radiation loss due to reduced sky factor (i.e., the building walls trap, or intercept, infrared radiation trying to escape up into the sky); 2) increased downward longwave radiation from the warmer air above the city (this may be due to trapping and re-emission from polluted layers aloft and/or from heat-island-induced vertical advection of warm surface air above the city); 3) increased shortwave absorption (the "bulk" albedo of urban areas is usually smaller than rural areas, possibly resulting from a combination of more surface area due to building walls and trapping of reflected solar radiation onto other urban surfaces due to canyon geometry); 4) decreased evapotranspiration due to less vegetation and moisture availability (this results in more energy going into heating the air and the canopy elements and less into latent heating of moisture); 5) anthropogenic heat input; 6) increased heat storage by canopy elements and 7) reduced heat transport (within the urban canopy the wind speeds and turbulent mixing are generally smaller).

Although decreased urban evapotranspiration, the anthropogenic heat flux, and the urban heat storage are major factors in the development of the urban heat island, it is difficult to draw general conclusions and the exact nature is site and time specific. For example, Oke[22] indicates that urban heat island development is a function of season (e.g., the anthropogenic heat flux increases in the winter for many northern latitude cities), the weather and local mesoscale flows (for example, seabreezes will interact with heat island development in coastal cities), local construction materials, local watering practices (for example, in downtown Mexico City it is common for the sidewalks to be cleaned every morning by hosing them down with water), and surrounding rural land use (e.g., rural areas surrounding arid southwestern U.S. cities will cool at a different rate than moist forest-covered midwestern and Atlantic seaboard cities).

Many of the factors cited above by Oke[22] are site and time dependent and have feedbacks with each other and with the flow field. Hence, it would be difficult to obtain universal functions for urban heat island intensity except for idealized cases. For modeling purposes, the individual factors need to be addressed in a robust way so that they interact reasonably. Several of the factors cited above are a strong function of the building height-to-width ratio (e.g., longwave radiation loss, shortwave absorption, wind speed, turbulent mixing) - which helps to explain the strong dependence of urban heat island intensity on urban density (see Fig. 7). For broad application in different urban environments, a mesoscale meteorological model should have urban canopy parameterizations capable of capturing the effects of urban density as a function of landuse type, for example. In Sections 3.4 and 3.5, we present methods that have been used to approximate the effect of the urban canopy on heat transport and the surface energy budget in mesoscale models. Next we look at another manifestation of the city on the atmosphere: urban roughness.

2.2 Urban roughness

From the macroscopic viewpoint, cities can be thought of as rough surfaces. When flying high over a city and looking down, one can understand why buildings are often considered to be surface roughness elements. Mesocale models "see" the world similarly. With grid sizes on the order of kilometers, buildings are not resolved and hence are often parameterized as surface roughness.

Increased surface roughness, generally associated with urban areas, leads to greater frictional momentum loss and increased turbulent fluxes of heat, momentum, and moisture. The review by Bornstein[1] reports that several field studies show wind speed deficits generally exist in urban areas, while turbulence levels are generally elevated. For example, the climatological annual mean wind speed for an expanding city in Russia decreased over time from 3.9 m/s in 1945 to 2.6 m/s in 1971. An elegant study by Hogstrom et al.[34] illustrates the impact of the urban area on the vertical profile of wind speed (Fig. 10). By placing an instrumented tower at the urban-rural interface and doing conditional sampling based on wind direction, average wind speed profiles were obtained for both urban and rural fetch wind directions. It is expected that the reduction in wind speed by surface roughness will be offset somewhat by the speed up of the wind associated with the urban heat island circulation.

Surface measurements analyzed by Bowne and Ball[35] revealed that urban turbulence levels in Fort Wayne, Indiana were 30 to 50% higher than rural levels. Bornstein[1] found that surface measurements in and

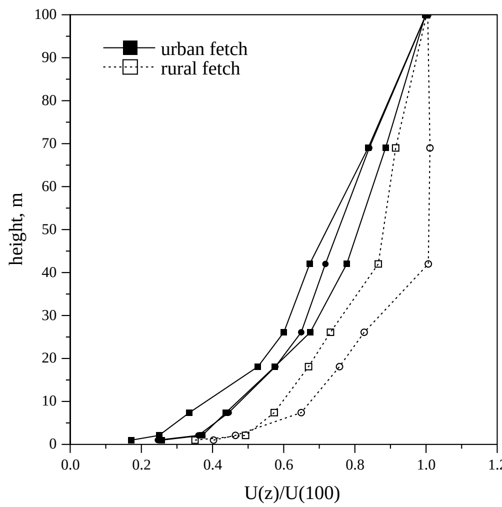

Figure 10. Average of many wind profiles measured on a tower during near-neutral conditions at an urban-rural interface (Hogstrom et al.[34]).

around New York City of the standard deviation of the horizontal wind direction σ_θ, a measure of turbulence intensity, indicated that values in the city were from 2 to 2.5 times greater than those in rural areas. Analysis of horizontal traverses over St. Louis by Godowitch[36] showed that the vertical velocity variance was about 50% larger as compared to outlying rural areas. It should be pointed out that these results include both the effects of urban heat island and roughness induced turbulence.

Wind-tunnel studies can isolate the surface roughness effect on wind and turbulence profiles. For example, Pendergrass and Arya[37] found that the mean velocity and Reynolds shear stress profiles for smooth surface and block roughness boundary layers were significantly different (Fig. 11). Theurer et al.[38] have performed a number of experiments over different configurations and shapes of building roughness elements. They found that wind speed and turbulence profiles above building rooftop are strongly impacted by the particular arrangement of buildings.

The studies cited above will be helpful in evaluating the wind and turbulence fields produced over cities. However, to understand the details of the parameterizations associated with urban roughness, it will be helpful to "zoom" down to the microscale and look explicitly at the flow fields around groups of buildings.

Numerous examples exist showing that wind flow patterns and turbulence mixing are dramatically altered around groups of buildings

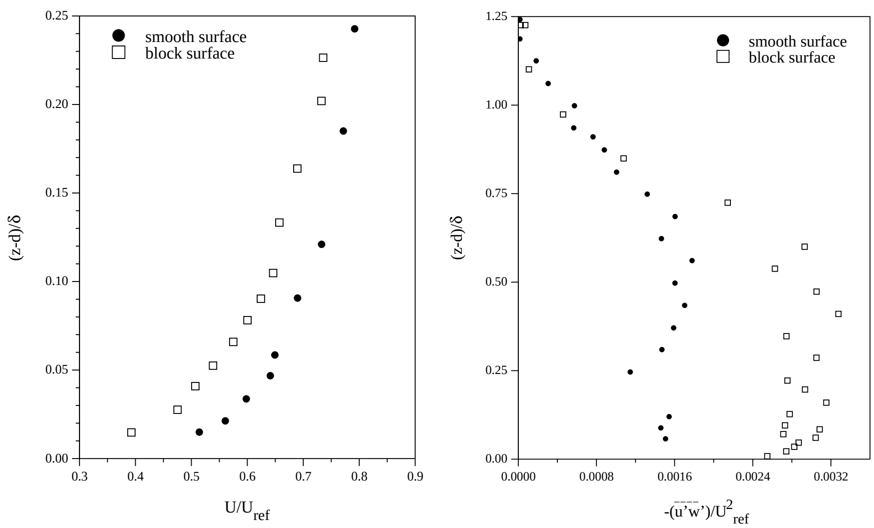

Figure 11. Comparison of non-dimensionalized mean wind profiles (left) and Reynolds shear stress profiles (right) for flow over a smooth surface and a block (urban) surface (Pendergrass and Arya[37]).

(e.g., Hosker[2]). Figure 12 depicts wind vectors and turbulence levels measured in a wind-tunnel around a rather simplified array of wide buildings. The measurements reveal vortices that form between the buildings in the street canyons, a jet region and recirculating flow above the first building rooftop, elevated turbulence levels above rooftop, and low turbulence levels in the street canyons. For rectangular buildings of equal height, the nature of the flow around the buildings is a function of the building width-to-height ratio. As summarized by Oke[22], a single vortex develops between buildings for skimming flow ($w/h < 1$), two counter-rotating vortices may develop for wake interference flow ($w/h \sim 1.5$), and for isolated roughness flow ($w/h > 3$) the flow field looks similar to the single building case (Fig. 13). Significantly more complicated flows can develop for groups of narrow buildings, for variable spacing between buildings, for buildings of different heights and shapes, and for different approach flow angles.

Few detailed mean and turbulence flow measurement campaigns have been performed within the real urban canopy. Roth[40] summarized

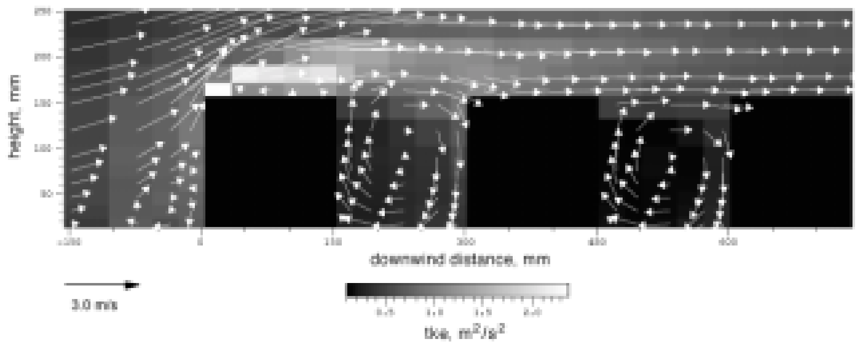

Figure 12. Wind vector and turbulent kinetic energy fields measured along centerline around a 2-d building array in the USEPA meteorological wind tunnel (Brown et al.[39]).

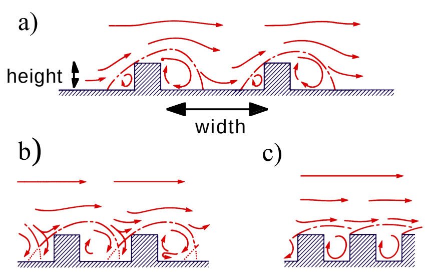

Figure 13. Flow regimes as function of width-to-height ratio: a) isolated roughness flow (w/h > 3); b) wake interference flow (w/h ~ 1.5); c) skimming flow (w/h < 1) (from Oke[22]).

results above the canopy layer in the so-called roughness sub-layer from 12 field experiments. He found that relationships derived from the logarithmic wind profile (see Section 3.2.2) described the data fairly well above the canopy height. Rotach[41] obtained a unique dataset containing vertical profiles of mean wind and turbulence statistics within and above an urban canopy in Zurich, Switzerland. Figure 14 shows mean wind and turbulent kinetic energy profiles averaged over many days of measurements. An inflection point is apparent in the mean wind profile, a signature of many vegetative canopy velocity profiles. Oikawa and Meng[42] measured mean wind and turbulence profiles in a suburban area in Sapporo, Japan that were in qualitative agreement with the

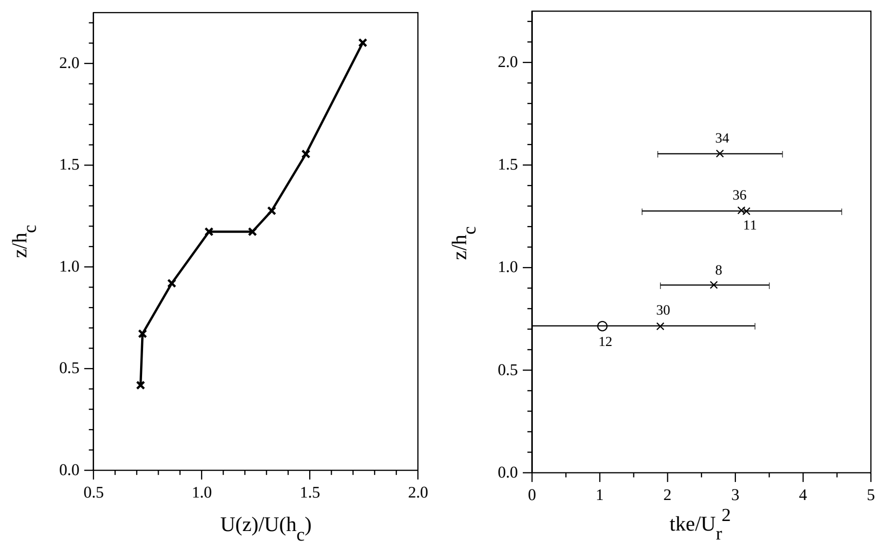

Figure 14. Average wind and turbulent kinetic energy profiles measured in a street canyon in Zurich (Rotach[41]). h_c is canopy height. Range and number of measurements are included on the tke plot.

measurements of Rotach[41]. They found that the Reynolds shear stress, a measure of the vertical turbulent momentum flux, peaked at about 1.5 times the canopy height.

As we have shown in this section, buildings act as a sink for momentum and result in a net loss of wind speed (see Section 3.2.1). The strong gradients in the wind produced by the buildings results in enhanced mechanical production of turbulence in the shear zones. The vertical variation of the area-average wind speed and tke is of course highly dependent on the arrangement, relative heights, and shapes of the buildings. For some applications, urban roughness parameterizations developed for mesoscale models should account for area-averaged drag and turbulent mixing effects and possibly be a function of the building geometry and configuration. In the next section, we discuss methods that have been developed for incorporating urban effects into mesoscale models.